Type-Ia Supernovae: New Clues to their Progenitors from the Delay Time Distribution

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Abstract. Despite their prominent role in cosmography, little is yet known about the nature of type-Ia supernovae (SNe Ia), from the identity of their progenitor systems, through the evolution of those systems up to ignition and explosion, and to the causes of the environmental dependences of their observed properties. I briefly review some of those puzzles. I then focus on recent progress in reconstructing the SN Ia delay time distribution (DTD) – the SN rate versus time that would follow a hypothetical brief burst of star formation. A number of measurements of the DTD over the past two years, using different methods and based on SNe Ia in different environments and redshift ranges, are converging. At delays $1 < t < 10$ Gyr, these measurements show a similar $\sim t^{-1}$ power-law shape, with similar normalizations. The DTD peaks at the shortest delays probed, but there is still some uncertainty regarding its precise shape in the range $0.1 < t < 1$ Gyr. At face value, this result supports Ron Webbinks's (1984) idea of a double-degenerate progenitor origin for SNe Ia, but the numbers currently predicted by binary population synthesis models must be increased by factors of 3-10, at least. Single-degenerate progenitors may still play a role in producing short-delay SNe Ia, or perhaps all SNe Ia, if there are fundamental errors in the current modeling attempts.

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WHAT WE DO NOT UNDERSTAND ABOUT TYPE-IA SUPERNOVAE

Supernovae (SNe) play a central role in astrophysics, not only as distance indicators for cosmology (e.g., Riess et al. 1998; Perlmutter et al. 1999), but as prime synthesizers of heavy elements (e.g. Woosley 2007), sources of kinetic energy, and accelerators of cosmic rays (e.g. Helder et al. 2009). However, many of the most basic facts about these events are still poorly understood. Type-Ia SNe (SNe Ia), the subject of this review, are linked by indirect evidence to the thermonuclear detonations of carbon-oxygen white dwarfs (WDs) whose masses have grown to near the Chandrasekhar limit (Hoyle & Fowler 1960). However, competing scenarios exist for the initial conditions and evolutionary paths that lead to this mass growth. In the single degenerate (SD) model (Whelan & Iben 1974), a WD grows in mass through accretion from a non-degenerate stellar companion. The double degenerate (DD) scenario, on the other hand, was first proposed in the landmark paper by Ron (Webbink 1984), the same paper we have seen referenced in so many of the talks at this meeting, on so many different topics. (The same idea was proposed simultaneously by Iben & Tutukov 1984). In this scenario, two WDs merge after losing energy and angular momentum to gravitational waves. To cite Ron in the abstract of that paper: “C/O-C/O pairs are again unstable to dynamical time-scale mass transfer and, since their masses exceed the Chandrasekhar limit, are destined to become SNe”.

Although 27 years have passed, neither the SD nor the DD models can yet be excluded observationally (nor clearly favored), and hence we find ourselves in an embarassing situation: these explosions are of the utmost astrophysical importance, we use them to reach radical conclusions about the existence and properties of dark energy, and yet we do not even know for sure *what* is exploding! Indeed, the recent Astronomy and Astrophysics Decadal Survey (`http://sites.nationalacademies.org/bpa/BPA_049810`) has listed determining the nature of SN Ia progenitors as one of the major objectives of the coming decade. Apart from the wide-open progenitor question, many questions remain regarding the subsequent phases: the details of the probably multiple accretion episodes; the enigmatic common-envelope phase; the type and the location of the ignition; the nature of the combustion – deflagration, detonation, or both; and within all of these details, the eventual causes of the regularities, trends, and environmental dependences observed in SN Ia light curves and spectra (see, e.g., the recent review by Howell 2010). Interestingly, even the near-Chandrasekhar-mass conjecture has come under renewed scrutiny. Sub-Chandrasekhar explosions have been proposed as a way of explaining some, or perhaps even most SN Ia events (Raskin et al. 2009; Rosswog et al. 2009; Sim et al. 2010; van Kekwijk, Chang & Justham 2010). Conversely, the Ni mass deduced for some SN Ia explosions is strongly suggestive of a super-Chandrasekhar-mass progenitor (e.g. Tanaka et al. 2010;

Silverman et al. 2010).

Both the SD and the DD models suffer from numerous problems, both theoretical and observational. In terms of SD theory, it has long been recognized that the mass accretion rate on to the WD needs to be within a narrow range, in order to attain stable hydrogen burning on the surface, and mass growth toward the Chandrasekhar mass. Too-low an accretion rate will lead to explosive ignition of the accreted hydrogen layer in a nova event, which likely blows away more material from the WD than was gained (e.g. Townsley & Bildsten 2005). Too-high an accretion rate will lead to the escape of the accreted material in a wind. The self-regulation of the accretion flow by the wind from the companion, as conceived by Hachisu & Nomoto (e.g. Hachisu et al. 1999) has thus long been considered to be an essential element of the SD model. Questions, however, have been raised as to whether the mechanism does not require too much fine tuning (Cassisi et al. 1998; Piersanti et al. 2000; Shen & Bildsten 2007).

The SD model faces additional obstacles when it comes to observational searches for its signatures. Badenes et al. (2007) searched seven young SN Ia remnants for the wind-blown cavities that would be expected in the wind-regulation picture. Instead, in every case it appeared the remnant is expanding into a constant-density ISM. Leonard (2007) obtained deep spectroscopy in the late nebular phase of several SNe Ia, in search of the trace amounts of H or He that would be expected from the stellar winds. None was found. Prieto et al. (2008) have pointed out the SNe Ia have been observed in galaxies with quite low metallicities. This may run counter to the expectations that, at low enough metallicities, the optical depth of the wind would become small, and the hence the wind-regulation mechanism would become ineffective. Variable NaD absorption has been detected in the spectra of a few SNe Ia (Patat et al. 2007; Simon et al. 2009) and has been interpreted as circumstellar material from the companion in an SD model. But why is such absorption seen in only a minority of cases searched? The companion, in an SD scenario, will survive the explosion, and is likely to be identifiable by virtue of its anomalous velocity, rotation, spectrum, or composition. However, searches for the survivor of Tycho's SN have not been able to reach a consensus (Ruiz Lapuente et al. 2004; Fuhrman 2005; Ihara et al. 2007; Gonzalez-Hernandez et al. 2009; Kerzendorf et al. 2009). Perhaps the effects of the explosion on the companion are more benign than once thought (see Pakmor et al. 2008). Hayden et al. (2010), however, place observational limits on the presence of any shock signatures in the light curves of 108 SNe Ia with good early-time coverage, shocks that are expected from the ejecta hitting the companion, as calculated by Kasen (2010). Finally, di Stefano (2010), and Gilfanov & Bogdan (2010), have raised related arguments that the accreting and growing WDs in the SD scenario would be undergoing stable nuclear burning on their surfaces, and hence would be visible as super-soft X-ray sources (SSS). The actual numbers of SSS are far below those required to explain the observed SN Ia rate.

The DD model is also not free of problems. Foremost, it has long been argued that the merger of two unequal-mass WDs will lead to an accretion-induced collapse and the formation of a neutron star, i.e. a core-collapse SN, rather than a SN Ia (Nomoto & Iben 1985; Guerrero et al. 2004). Others, however, have argued for ways to avoid this outcome (Piersanti et al. 2003; Pakmor et al. 2010; Van Kerkwijk et al. 2010). Observationally, it has been much harder to find evidence either for or against the DD scenario because, by construction, it leaves essentially no traces – it is the perfect crime! The most promising avenue has been to search the Solar neighborhood for the close and massive WD binaries that will merge within a Hubble time, surpassing the Chandrasekhar mass and presumably producing DD SNe Ia. The largest survey to date, SPY (Napiwotzki et al. 2004; Geier et al. 2007) has found no such pairs among ~ 1000 WDs. However, only of order one pair is probably expected given the (highly uncertain) Galactic SN Ia rate (Maoz 2008). Clearer results may emerge from the ongoing SWARMS survey by Badenes et al. (2009), which searches for close binaries among an order of magnitude more WDs in the Sloan Digital Sky Survey.

There are additional problems that are shared by both scenarios, SD and DD. The energetics and spectra of the explosions do not come out right, unless finely (and artificially) tuned in an initial subsonic deflagration that, at the right point in time, spontaneously evolves into a supersonic detonation (Khokhlov 1991). If the ignited mass is always near-Chandrasekhar, why is there the range of SN Ia luminosities inherent to the Phillips (1993) relation? (Indeed, Sim et al. 2010 show that their sub-Chandrasekhar models do a fair job of reproducing the Phillips relation). Why is there a dependence of the SN Ia luminosity (or, equivalently, the mass of radioactive Ni synthesized) on the age of the galaxy host (e.g. Howell et al. 2009)? The oldest hosts, with little star formation, are clearly observed to host only faint, low-stretch, SNe Ia, while star-forming galaxies host both bright-and-slow and faint-and-fast SNe Ia. Finally, both scenarios predict, based on binary population synthesis, SN rates that are lower than actually observed (more on this later).

THE DELAY-TIME DISTRIBUTION

A fundamental function that can shed light on the progenitor question is the SN delay time distribution (DTD). The DTD is the hypothetical SN rate versus time that would follow a brief burst of star formation. The DTD is directly linked to the lifetimes (i.e., the initial masses) of the progenitors and to the binary evolution timescales up to the explosion, and therefore different progenitor scenarios predict different DTDs. Various theoretical forms have been proposed for the DTD, some derived from detailed binary population synthesis calculations (e.g., Yungelson & Livio 2000; Han & Podsiadlowski 2004; Ruiter et al. 2009; Mennekens et al. 2010; see also contributions to this volume by Claeys, Mennekens, Ruiter, Toonen, and Wang); some physically motivated mathematical parameterizations, with varying degrees of sophistication (e.g., Madau et al. 1998; Greggio 2005; Totani et al. 2008); and some ad hoc formulations intended to reproduce the observed field SN rate evolution (e.g., Strolger et al. 2004).

Until recently, only few, and often-contradictory, observational constraints on the DTD existed. In the past year or so, the observational situation is changing dramatically, and a clear view of the DTD is emerging, one that is beginning to discriminate among SN Ia progenitor models. I review these observations, with emphasis on the most recent ones.

SN Ia rates versus redshift, compared to cosmic star-formation history

One observational approach to recovering the DTD has been to compare the SN rate in field galaxies, as a function of redshift, to the cosmic star formation history (SFH). Given that the DTD is the SN "response" to a short burst of star formation, the SN rate versus cosmic time, $R_{Ia}(t)$, will be the convolution of the DTD with the SFH (i.e. the star formation rate versus cosmic time), $S(t)$,

$$R_{Ia}(t) \propto \int_0^t S(t-\tau)\frac{\Psi(\tau)}{m(\tau)}d\tau, \tag{1}$$

where $m(\tau)$ is the surviving mass fraction in a stellar population, after accounting for the mass losses during stellar evolution due to SNe and winds (and is obtainable from stellar population synthesis models). Here and throughout, we will be considering SN rates measured per unit stellar mass *at the time of observation*, and DTDs normalized per unit stellar mass *formed*. In making intercomparisons of measurements among themselves, and with predictions, I have taken special care that consistent definitions and stellar initial mass functions (IMFs) be assumed.

Gal-Yam & Maoz (2004) carried out the first such comparison, using a small sample of SNe Ia out to $z = 0.8$, and concluded that the results were strongly dependent on the poorly known cosmic SFH, a conclusion echoed by Forster et al. (2006). With the availability of SN rate measurements to higher redshifts, Barris & Tonry (2006) found a SN Ia rate that closely tracks the SFH out to $z \sim 1$, and concluded that the DTD must be concentrated at short delays, < 1 Gyr. Similar conclusions have been reached, at least out to $z \sim 0.7$, by Sullivan et al. (2006). In contrast, Dahlen et al. (2004, 2008) and Strolger et al. (2004, 2010) have argued for a DTD that is peaked at a delay of ~ 3 Gyr, with little power at short delays, based on a sharp decrease in the SN Ia rate at $z > 1$ found by them in the HST/GOODS survey. However, Kuznetzova et al. (2007) re-analyzed some of these datasets and concluded that the small numbers of SNe and their potential classification errors preclude reaching a conclusion. Similarly, Poznanski et al. (2007) performed new measurements of the $z > 1$ SN Ia rate by surveying the Subaru Deeep Field with the Subaru SuprimeCam. We found that, within uncertainties, the SN rate could be tracking the SFH. This, again, would imply a short delay time. Greggio et al. (2008) pointed out that underestimated extinction of the highest-z SNe, observed in their rest-frame ultraviolet emission, could be an additional factor affecting these results. Blanc & Greggio (2008) and Horiuchi & Beacom (2010) have shown that, within the errors, a wide range of DTDs is consistent with the data, but with a preference for a DTD similar to $\sim t^{-1}$.

Happily, at the time of this writing, it appears that the picture is finally clarifying and converging with respect to the field SN Ia rate as a function of redshift, and the DTD that it implies. Rodney & Tonry (2010) have presented a re-analysis of the data of Barris & Tonry (2006), with new SN Ia rates that are lowered, and in much better agreement with other measurements at similar redshifts. Preliminary new rates from the Supernova Legacy Survey (Perrett et al., in preparation) agree with the revised numbers, and suggest a SN Ia rate that continues to rise out to $z = 1$, albeit growing more gradually than the SFH. Finally, a quadrupling of the initial high-z SN sample, first presented by Poznanski et al. (2007), is resolving the puzzle of the SN rate out to $z = 2$. Graur et al. (in preparation) present a sample of 150 SNe discovered by "staring" at a single Subaru SuprimeCam field – the Subaru Deep Field – at four independent epochs, with 2 full nights of integration per epoch. SN host galaxy redshifts are based on spectral and photometric redshifts,

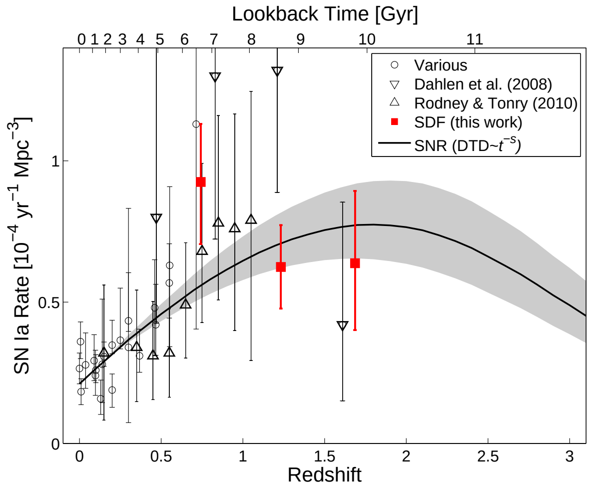

FIGURE 1. SN Ia rate versus redshift. Filled squares (red) are from the Subaru Deep Field search by Graur et al. (in preparation). The curve is obtained by convolving the SFH of Hopkins & Beacom (2006) with a DTD of the form $\Psi(t) \propto t^{-1}$.

from the extensive UV to IR database existing for this field. Classification of the SN candidates is photometric. The SN sample includes 26 events that are fully consistent with being normal SNe Ia in the redshift range $1.0 < z < 1.5$, and 10-12 such events at $1.5 < z < 2.0$. The rates derived from the Subaru data merge smoothly with the most recent and most accurate rate measurements at $z < 1$, confirming the trend of a SN Ia rate that gradually levels off at high z, but does not dive down, as previously claimed by Dahlen et al. (2004, 2008). In Graur et al., we find that a DTD with a power-law form, $\Psi(t) \propto t^{-1}$, when convolved with the Hopkins & Beacom (2006) SFH, gives an excellent fit to the observed SN rates. The rates and this fit are shown in Fig. 1.

SN Ia rate versus galaxy "age"

Another approach to recovering the DTD has been to compare the SN rates in galaxy populations of different characteristic ages. Using this approach, Mannucci et al. (2005, 2006), Scannapieco & Bildsten (2005), and Sullivan (2006) all found evidence for the co-existence of two SN Ia populations, a "prompt" population that explodes within $\sim 100-500$ Myr, and a delayed channel that produces SNe Ia on timescales of order 5 Gyr. This has led to the "$A+B$" formulation which, in essence, is just a DTD with two coarse time bins. The B parameter, divided by the assumed duration of the prompt component, is the mean SN rate in the first, prompt, time bin of the DTD. The A parameter is (after correcting for stellar mass loss, $m(t)$) the mean rate in the second, delayed, time bin. Naturally, these two "channels" may in reality be just integrals over a continuous DTD on two sides of some time border (Greggio et al. 2008). Totani et al. (2008) have used a similar approach to recover the DTD, by comparing SN Ia rates in early-type galaxies of different characteristic ages, seen at $z = 0.4-1.2$ as part of the Subaru/XMM-Newton Deep Survey (SXDS) project. They find a DTD consistent with a t^{-1} form. Additional recent attempts to address the issue with the "rate vs. age" approach have been made by Aubourg et al. (2008), Raskin et al. (2009), Yasuda & Fukugita (2009), and Cooper et al. (2009).

SN Ia rate versus individual galaxy star formation histories

Both of the approaches described above involve averaging, and hence some loss of information. In the first approach, one averages over large galaxy populations, by associating all of the SNe detected at a given redshift with all the galaxies of a particular type at that redshift. In the second approach, a characteristic age for a sample of galaxies replaces the detailed SFH of the individual galaxies in a SN survey. Maoz et al. (2010a) recently presented a method for recovering the DTD, which avoids this averaging. In the method, the SFH of every individual galaxy, or even galaxy

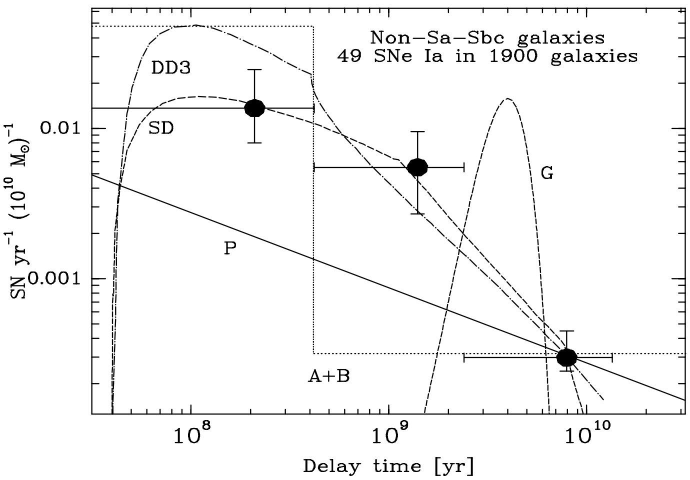

FIGURE 2. DTD recovered by Maoz et al. (2010a) from a subsample of the Lick Observatory SN Search galaxies and their SNe, based on the individual SFH of each galaxy from its SDSS spectrum. The example shown uses a subsample excluding intermediate Hubble types, which are prone to incorrect representation of the full SFH of the galaxy, due to the limited aprture of the SDSS spectrograph fibers. The observed DTD is compared to several theoretical and observed DTDs: the $t^{-0.5}$ power law proposed by Pritchet et al. (2008; P); the Gaussian DTD found by Dahlen et al. (2004, 2008; G); SD and DD analytic models by Greggio (2005); and the DTD implied by the A+B picture of Scannapieco & Bildsten (2005).

subunit, is compared to the number of SNe it hosted in the survey (generally none, sometimes one, rarely more). DTD recovery is treated as a linearized inverse problem, which is solved statistically. Maoz et al. (2010a) applied the method to a subsample of the galaxies, and the SNe they hosted, in the Lick Observatory SN Search (LOSS; Leaman et al. 2010; Li et al. 2010a,b). This has been that largest survey for local (<200 Mpc) SNe over the past 15 years. From the 15,000 LOSS survey galaxies, we chose subsamples having spectral-synthesis-based SFH reconstructions by Tojeiro et al. (2009), based on spectra from the Sloan Digital Sky Survey (SDSS; York et al, 2000). In the recovered DTD (Fig. 2) Maoz et al. (2010a) find a significant detection of both a prompt SN Ia component, that explodes within 420 Myr of star formation, and a delayed SN Ia with population that explodes after > 2.4 Gyr. A related DTD reconstruction method has been applied by Brandt et al. (2010) to the SNe Ia from the SDSS II survey. Like Maoz et al. (2010a), they detect both a prompt and a delayed SN Ia population.

SN remnants in nearby galaxies with SFHs based on resolved stellar populations

Another application of the idea to reconstruct the DTD while taking into account SFHs, rather than mean ages, was made by Maoz & Badenes (2010). We applied this method to a sample of SN remnants in the Magellanic Clouds, which we compiled in Badenes, Maoz, & Draine (2010). The Clouds have very detailed SFHs in many small individual spatial cells, obtained by Harris & Zaritsky (2004, 2009), by fitting model stellar isochrones to the resolved stellar populations. Thus, one can compare the SFH of each individual cell to the number of SNe it hosted (or did not) over the past few kyr, as evidenced by the observed remnants. This turns the remnants in the Clouds into an effective SN survey, although several complications need to be dealt with (see Badenes et al. 2010 and Maoz & Badenes 2010). Using this method, we again find a significant detection of a prompt (this time < 330 Myr) SN Ia component. We are currently producing larger samples by using the SN remnant populations in additional nearby galaxies, such as M33 and M31, and their spatially resolved SFHs, again based on the resolved stellar populations.

A frequent objection that arises, when considering this approach, is that one cannot correctly deduce SN delay times by comparing, on the one hand, star formation rates in a small projected piece of a galaxy to, on the other hand, the SNe that this region of the galaxy is seen to host, since random velocities cause the SN progenitor, by the time it explodes, to have drifted far from its birth location. While this objection is indeed valid if one is comparing SNe to the mean ages of their locations, it does not apply if, as here, we are considering detailed SFHs (rather than mean ages), for full ensembles of galaxy cells and SNe. The reason is that both the SN progenitors and their entire parent

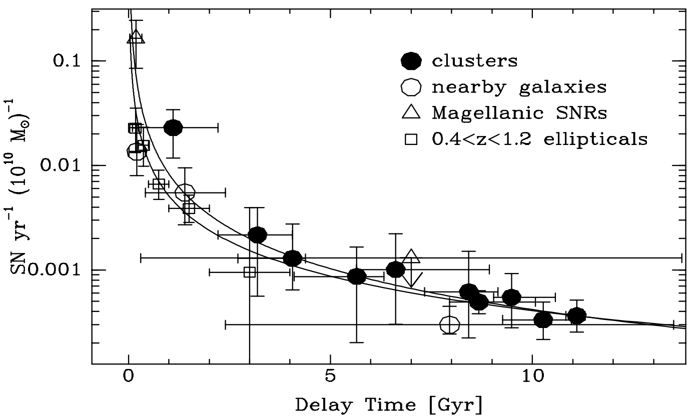

FIGURE 3. Filled points: SN Ia DTD recovered based on galaxy cluster SN Ia rate measurements, and cluster iron abundances, from Maoz et al. (2010b). Also shown are some of the DTD derivations previously described, using other methods, in different environments and different redshifts. The solid curves are power laws, $t^{-1.1}$ and $t^{-1.3}$, that describe well these results, as well as the latest field SN Ia rate measurements out to $z = 2$, when compared to the cosmic SFH (see Fig. 1).

populations undergo the same spatial diffusion within a galaxy over time. This is explained in more detail in Maoz et al. (2010a) and Maoz & Badenes (2010).

SN Ia rates versus redhsift in galaxy clusters

The last approach I will review for recovering the DTD is to measure the SN rate vs. redshift in massive galaxy clusters. The deep potential wells of clusters, combined with their relatively simple SFHs, make them ideal locations for studying both the DTD and the metal production of SNe. Optical spectroscopy and multiwavelength photometry of cluster galaxies has shown consistently that the bulk of their stars were formed within short episodes (~ 100 Myr) at $z \sim 3$ (e.g., Daddi et al. 2000; Stanford et al. 2005; Eisenhardt et al. 2008). Thus, the observed SN rate vs. cosmic time t, given a stellar formation epoch t_f, provides an almost direct measurement of the form of the DTD,

$$R_{Ia}(t) = \frac{\Psi(t-t_f)}{m(t-t_f)}. \tag{2}$$

Furthermore, the record of metals stored in the intracluster medium (ICM) constrains the integrated number of SNe Ia per formed stellar mass, $N_{\rm SN}/M_*$, that have exploded in the cluster over its stellar age, t_0, and hence the normalization of the DTD,

$$\int_0^{t_0} \Psi(t)dt = \frac{N_{\rm SN}}{M_*}. \tag{3}$$

As reviewed in detail in Maoz et al. (2010b), X-ray and optical observations of galaxy clusters have reached the point where they constrain $N_{\rm SN}/M_*$ to the level of $\pm 50\%$, based on the observed abundances of iron (the main product of SN Ia explosions), after accounting for the contributions by core-collapse SNe (and the uncertainty in that contribution).

A decade ago, there were no real measurements of SN rates in galaxy clusters. However, the observational situation has again improved dramatically, especially in the last few years. Following large investments of effort and observational resources, fairly accurate cluster SN Ia rates have now been measured in the redshift range from $0 < z < 1.5$ (Gal-Yam et al. 2002,2008; Sharon et al. 2007, 2010; Mannucci et al. 2008; Graham et al. 2008; Dilday et al. 2010; Barbary et al. 2010). Figure 3 shows (filled points) the DTD derived by Maoz et al. (2010b) based on these galaxy-cluster SN Ia rate measurements, together with the iron-based DTD integral constraint, which sets the level in the earliest DTD bin. Also plotted, with open symbols, are some of the recent DTD measurements described previously: the DTD from the ages of high-z field ellipticals (Totani et al. 2008); the DTD from the nearby LOSS galaxies and

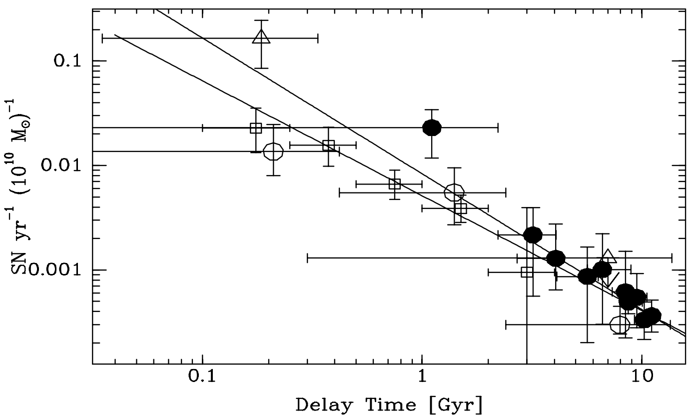

FIGURE 4. Same as Fig. 3, but with a logarithmic time axis

their SDSS-based SFHs (Maoz et al. 2010a, Fig. 2); the DTD from the Magellanic Cloud SN remnants by Maoz & Badenes (2010); and (solid curves) the power-law DTDs that best fit the high-*z* field SN rates in the Subaru Deep Field, by Graur et al., when compared to the cosmic SFH (see Fig. 1). Figure 4 shows the same data, but on a logarithmic time axis that illustrates more clearly the situation at short time delays.

SYNTHESIS

The picture emerging from Figs. 3-4 is remarkable. For one, all of these diverse DTD determinations, based on different methods, using SNe Ia in different environments and at different redshifts, agree with each other, both in form and in absolute level. At delays $t > 1$ Gyr, there seems little doubt that the DTD is well described by a power law of the form t^{-s}, with $s \approx 1$. The union of the 95% confidence ranges resulting from the detailed statistical analyses in the papers above is $0.9 < s < 1.5$. At delays $t < 1$ Gyr, the picture is not as clear cut. Nonetheless, it *is* clear that the DTD does peak in that earliest time bin. It may continue to rise to short delays with the same slope seen at long delays, or it may transit to a shallower rise, but it certainly does not fall. The explosion of at least $\sim 1/2$ of SNe Ia within 1 Gyr of star formation is, by now, probably an inescapable fact.

Apart from the form of the DTD, there is also fairly good agreement, among all the derivations, on its normalization, or equivalently, its integral over a Hubble time. Once due attention is given to consistent definitions and assumptions of IMF (see above), the time-integrated number of SNe Ia per stellar mass formed is in the range of $N_{\rm SN}/M_* = (1.5-3.5)\times 10^{-3}\,{\rm M_\odot}^{-1}$, assuming a realistic IMF, with a turnover at low stellar masses.

What does this observed DTD imply for the burning questions on the progenitors of SNe Ia? Power laws have been long considered as possible forms of the DTD (e.g., Ciotti et al. 1991; Sadat et al. 1998). As noted by previous authors (e.g., Greggio 2005; Totani et al. 2008) a power-law dependence is generic to models (such as the DD model) in which the event rate ultimately depends on the loss of energy and angular momentum to gravitational radiation by the progenitor binary system. If the dynamics are controlled solely by gravitational wave losses, the time t until a merger depends on the binary separation a as

$$t \sim a^4. \tag{4}$$

If the separations are distributed as a power law

$$\frac{dN}{da} \sim a^{\varepsilon}, \tag{5}$$

then the event rate will be

$$\frac{dN}{dt} = \frac{dN}{da}\frac{da}{dt} \sim t^{(\varepsilon-3)/4}. \tag{6}$$

For a fairly large range around $\varepsilon \approx -1$, which describes well the observed distribution of initial separations of non-interacting binaries (see Maoz 2008 for a review of the issue in the present context), the DTD will have a power-law dependence with index not far from -1. Indeed, a $\sim t^{-1}$ power law appears to be a generic outcome also of detailed binary population synthesis calculations of the DD channel (e.g., Yungelson & Livio 2000; Mennekens et al. 2010; see Toonen, Claeys in this volume). However, in reality, the binary separation distribution of WDs that have emerged from their common envelope phase could be radically different, given the complexity of the physics of that phase. Thus, the $\sim t^{-1}$ DTD dependence of the DD channel cannot be considered unavoidable. Be that as it may, the observed DTD reconstructions all point to a $\sim t^{-1}$ power-law.

A different power-law DTD dependence, with different physical motivation, has been proposed by Pritchet et al. (2008). If the time between formation of a WD and its explosion as a SN Ia is always brief compared to the formation time of the WD, the DTD will simply be proportional to the formation rate of WDs. Assuming that the main-sequence lifetime of a star depends on its initial mass, m, as a power law,

$$t \sim m^{\delta}, \tag{7}$$

and assuming the IMF is also a power law,

$$\frac{dN}{dm} \sim m^{\lambda}, \tag{8}$$

then the WD formation rate, and hence the DTD, will be

$$\frac{dN}{dt} = \frac{dN}{dm}\frac{dm}{dt} \sim t^{(1+\lambda-\delta)/\delta}. \tag{9}$$

For the commonly used value of $\delta = -2.5$ and the Salpeter (1955) slope of $\lambda = -2.35$, the resulting power-law index is -0.46, or roughly $-1/2$. Pritchet et al. (2008) raised the possibility of such a $t^{-1/2}$ DTD. It is arguable that, instead of a single, $\sim t^{-1}$ power law, motivated by binary mergers, with this power law extending back to delays as short as 40 Myr (the lifetime of the most massive stars that form WDs), there could be a "bottleneck" in the supply of progenitor systems below some delay. Such a bottleneck could be due to the birth rate of WDs, which behaves as $\sim t^{-1/2}$. One possible result would then be a broken-power-law DTD, with $\Psi \propto t^{-1/2}$ up to some time, t_c, and $\Psi \propto t^{-1}$ thereafter. A possible value could be $t_c \approx 400$ Myr, corresponding to the lifetimes of $3M_{\odot}$ stars. If that were the lowest initial mass of stars that can produce the WD primary in a DD SN Ia progenitor, then beyond t_c the supply of new systems would go to zero, and the SN Ia rate would be dictated by the merger rate. Indeed, the Greggio (2005) DD model, shown in Fig. 2, above, is essentially a $t^{-1/2}$, $t^{-1.3}$, broken power-law with break at $t_c < 400$ Myr. The detailed fits to the various observational DTDs show that such broken power laws are acceptable, as long as $t_c < 1.5$ Gyr. Such a late break time is interesting in the context of sub-Chandra merger models, in which the mergers of white dwarfs that had main sequence masses smaller than $3M_{\odot}$ can produce SNe Ia (Sim et al. 2010; Van Kerkwijk et al. 2010).

In terms of the observed DTD normalizations, the DD models do not fare as well. As already noted by Maoz (2008), Ruiter et al. (2008), Mennekens et al. (2010), and Maoz et al. (2010b), binary synthesis DD models underpredict observed SN rates by factors of at least a few, and likely by more. It is not clear at present if there is a good way to alleviate this inconsistency with the observations.

While the DTD predicted by Ron's DD model appears to be supported by the observations, at least in terms of form, if not normalization, the situation is quite different for the SD scenario. There is a staggering variety of results among the predictions for the DTD from SD models. Some of this variety is due to the fact that "SD" includes an assortment of very different sub-channels. Some of it is due to the fact that, even within a given sub-channel, different workers treat the same evolutionary phases using different approximations (e.g. the common-phase phase, via Ron's α formalism, or Neleman & Tout's 2005 γ parameter). And some of of the variety is due the use of different assumed input parameters and distributions. But, disturbingly, attempts by some teams (e.g. Mennekens et al. 2010) to reproduce results of other teams by using the same recipes and inputs still show significant discrepancies. Under this state of affairs, it appears that the theoretical SD predictions for the DTD have not yet reached the point where they can be meaningfully compared to the observations. One generic prediction that SD models do seem to make, however, is that the DTD tends to drop off to zero well before a Hubble time. If this is correct (and it may well not be; Phillip Podsiadlowski has often pointed out that the BPS calculations also fail to predict adequate numbers of other binary populations that we know do exist), this would mean that SD SNe Ia do not play a role in producing the DTD tail clearly seen at long delays in the observations. However, the present data cannot exclude also an SD contribution at short delays, present in tandem with a DD component that produces the t^{-1} power law DTD at long delays.

In summary, a host of measurements over the past few years have revealed an increasingly clear picture of the SN Ia DTD. It is well described by a power law of index -1, or somewhat steeper, going out to a Hubble time. At delays of < 1 Gyr, this shape may continue, or the slope may become somewhat shallower. The time-integrated SN Ia production efficiency is one SN Ia event for every $500 M_{\odot}$ formed in stars, accurate to better than a factor of 2. The observed DTD form is strikingly similar to the form generically expected, due to fundamental gravitational wave physics, from Ron Webbink's (1984) DD idea. The efficiency of SN Ia production by detailed models still falls short of the observed number, by at least a factor of a few. The competing SD model makes predictions that differ from the observations both in DTD form and in the absolute numbers of SNe. Given the disagreement among the SD calculations themselves, it is not yet clear if this is a problem of the SD model or of its calculation. But, keeping all these caveats in mind, the current picture appears to be a "thumbs up" to Ron's model!

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